(54) Title: A SYSTEM AND METHOD FOR A DIGITAL MASS FLOW CONTROLLER
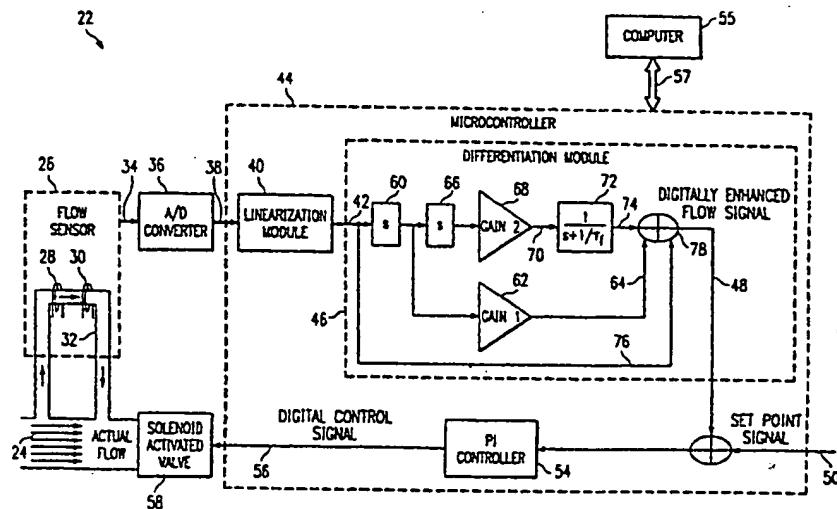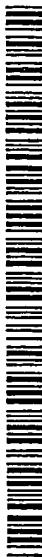
(57) Abstract: A method for controlling the gas flow within a digital mass flow controller. The method calculates a digitally enhance flow rate signal that more accurately represents an actual flow rate through the digital mass flow controller. The digitally enhanced flow rate is calculated using a sensed flow rate signal output from a flow sensor, a scaled first derivative of the sensed flow rate signal, and a scaled, filtered second derivative of the sensed flow rate signal. A set-point signal is compared to the digitally enhanced flow rate signal to generate a digital error signal. The digital error signal is provided to a digitally realized PI (proportional integral) controller. The PI controller generates a digital control signal which is used to control a valve in the digital mass flow controller.

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A SYSTEM AND METHOD FOR A
DIGITAL MASS FLOW CONTROLLER

TECHNICAL FIELD OF THE INVENTION

5   This invention relates generally to a method and
system for controlling the flow of gas in a mass flow
controller and more specifically to a method and system
for generating a digital control signal with a fast
response to set point step input in a digital mass flow
10   controller.

2.

BACKGROUND OF THE INVENTION

A mass flow controller (MFC) is a closed loop device
that sets, measures, and controls the flow of the mass of
a process gas. Semiconductor applications have been and
5   continue to be the driving force behind product
development in mass flow controller technology.
Nonetheless, mass flow control is useful in other
industries such as the pharmaceutical industry and food
industry.

10   A thermal mass flow controller is composed of a
front half which includes a flow sensor and a back half
which includes a control valve. The flow sensor is often
composed of two resistance temperature sensors wound
around a capillary tube. When gas flows through the
15   sensor, heat is carried downstream and the temperature
difference is proportional to the mass flow rate of the
gas. The control valve receives a signal via electronics
from the flow sensor to regulate gas flow. Solenoid
activated valves are often used as control valves because
20   of their simplicity, quick response, robustness and low
cost.

Unfortunately, thermal flow sensors have a slow
response time since thermal changes take place over a
relatively long period of time. For instance, in
25   FIGURE 1, a graphical representation of an actual flow
versus time is shown alongside a graphical representation
of sensed flow versus time. The y-axis indicates flow
rate while the x-axis indicates time. The actual flow is
represented as an approximation to a unit step function
30    $u(t)$ where the flow rate reaches a steady state value

3.

within a negligible amount of time. τ is denoted as the
time constant it takes for the sensed flow to reach 63%
of the actual flow. This may be as much as 1.7 seconds.
It takes approximately 5τ to reach at least 99% of the
5   actual flow. Unfortunately, the time delay needed to
establish an accurate measurement of the actual flow from
the sensed flow can introduce errors in the valve
control. Information regarding the flow rate through the
control valve is fed back to the control valve. Delay in
10 accurate feedback of this information may contribute to
undesirable errors in the flow of gas into a process
chamber.

FIGURE 2 represents a method used in the prior art
to compensate for the time delay in the sensed flow as
15 compared to the actual flow. The actual flow is a unit
step function of magnitude f_0. FIGURE 2 shows a first
derivative feedback control loop 10 where a flow sense
signal 12 is input into both a first gain stage 14, with
gain=1, and a differentiator stage 16. The output of the
20 differentiator 16 is input into a second gain stage 18,
with gain=τ. The output of gain stage 14 and gain stage
18 are added to produce output 20 of first derivative
feedback control loop 10.

This method approximates flow signal 12 as an
25 exponential signal given by,

$$f(t) = f_0(1 - e^{\frac{t}{\tau}}),$$ eqn. 1

4.

where f_o is the final steady state flow rate, t is the
time and τ is the time constant associated with the flow
sensor. The output 20 is given by,

$$output = f(t) + \tau\frac{df(t)}{dt}.$$ eqn. 2

5   Inserting eqn. 1 into eqn. 2 yields

$$output = f_o\, u(t).$$ eqn. 3

The output of first derivative feedback control system 10
is a step response of magnitude f_o that is equal to the
actual flow $f_o\, u(t)$. Therefore the actual flow is more
10   closely approximated using first derivative feedback
control system 10 than using just sensed flow signal 12.

The prior art method detailed in FIGURE 2 has three
disadvantages. The first disadvantage is that flow
sensors typically do not exhibit linear behavior.
15   Therefore, there is a certain amount of error innate in
the flow sensor signal that is input into a control
system.

The second disadvantage is that differentiator is
typically an analog device. Hardware implementation of a
20   differentiation device is difficult to realize in the
analog domain and consequently these methods often use
approximate differentiation implemented by linear
circuits.

Lastly, first derivative feedback control systems
25   fail to recognize that the flow of gas through the mass
flow controller is really not a true first order

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exponential. Therefore, there is a certain amount of
error innate to this type of system.

Ultimately, there is a need for a method that
accurately calculates the actual gas flow within a mass
5   flow controller. The method should reduce or eliminate
the non-linearities of the flow sensor. This method
should also more accurately approximate the flow sense
signal which is not a true exponential signal.

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SUMMARY OF THE INVENTION

       The present invention provides a system and method
for controlling gas flow within a digital mass flow
controller that substantially eliminates or reduces

5   disadvantages and problems associated with previously
developed systems and methods for controlling gas flow
within a digital mass flow controller.

       The present invention provides a method that
calculates a digitally enhanced flow rate signal that

10   more accurately represents an actual flow rate through
the digital mass flow controller. The digitally enhanced
flow rate signal is calculated using a sensed flow rate
signal output from a flow sensor, a scaled first
derivative of the sensed flow rate signal, and a scaled

15   second derivative of the sensed flow rate signal. A set-
point signal is compared to the digitally enhanced flow
rate signal to create a digital error signal. The
digital error signal is provided to a digitally realized
PI (proportional integral) controller. The PI controller

20   generates a digital control signal that is used to
control a valve in the digital mass flow controller.

       One advantage of the present invention is that the
use of a second derivative enables a more accurate
approximation of the sensor signal than the use of a

25   first derivative alone. A more accurate approximation of
the sensor flow rate signal enables a more precise and
responsive control of the gas flow in a process.

       Another advantage of the present invention is that
the use of digital signals readily enables interfacing

30   with digital processors such as computers. High speed

digital processors can be accessed to aid in rigorous
computations, during calibration for example, which may
be too lengthy for any on-board DSP controller in the
mass flow controller.

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BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention and the advantages thereof may be acquired by referring to the following description, taken in conjunction with the accompanying drawings in which like reference numbers indicate like features and wherein:

FIGURE 1 illustrates the output of a flow sensor in comparison to the actual flow rate in a mass flow controller vs. time;

FIGURE 2 is a basic control diagram of prior art methods of analog first differentiation and feedback to better approximate the actual flow from the sensed flow;

FIGURE 3 is one embodiment of the present invention illustrating a system for a digital mass flow controller;

FIGURE 4 is a graphical representation of the effects of the first gain stage on a continuous representation of the digitally enhanced flow rate signal;

FIGURE 5 is a graphical representation of the effects of the second gain stage on a continuous representation of the digitally enhanced flow rate signal; and

FIGURE 6 is a graphical representation of the effects of the filter time constant on a continuous representation of the digitally enhanced flow rate signal.

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DETAILED DESCRIPTION OF THE INVENTION

Preferred embodiments of the present invention are illustrated in the figures, like numerals being used to refer to like and corresponding parts of various

5   drawings.

The present invention provides a method for controlling the gas flow within a digital mass flow controller. The method calculates a digitally enhanced flow rate signal that more accurately represents an

10   actual flow rate through the digital mass flow controller. The digitally enhanced flow rate signal is calculated using a sensed flow rate signal output from a flow sensor, a scaled first derivative of the sensed flow rate signal, and a scaled second derivative of the sensed

15   flow rate signal. A set-point signal is compared to the digitally enhanced flow rate signal to create a digital error signal. The digital error signal is provided to a digitally realized PI (proportional integral) controller. The PI controller generates a digital control signal

20   which is used to control a valve in the digital mass flow controller.

FIGURE 3 represents one embodiment of the present invention. In FIGURE 3, actual flow 24 in mass flow controller 22 is measured by sensor 26. Sensor 26 may

25   include two resistive wound coils 28 and 30 wrapped around capillary tube 32. Sensor 26 outputs are the sensed flow rate signal 34 which can be input into A-to-D converter 36. The output of the A-to-D converter 36 is digital sensed flow signal 38. Digital sensed flow

30   signal 38 is input into microcontroller 44.

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Microcontroller 44 is programmed to perform the
computational requirements of the processes represented
by linearization module 40, differentiation module 46,
and PI controller 54. Microcontroller 44, a digital

5   signal processor (DSP) controller, has software
programmed in its on-chip flash program memory array that
can be reprogrammed multiple times. The software
incorporates all the instruction necessary to the
implementation of the functions described within

10   microcontroller 44. The constant coefficients (filter
coefficients, linearization coefficients, and various
gain factors) are computed in computer 55 and downloaded
for microcontroller 44 to use. Linearization module 40
may implement a least squares method to linearize digital

15   flow signal 38. Digital sensed flow signal 38 needs to
be linearized since sensor 26 generally produces a sensed
flow signal 34 that is a non-linear function of actual
flow 24. Linearization module 40 outputs digitally
linearized sensed flow signal 42. There are many methods

20   for linearization of the digital sensed flow signal.
These methods include least squares methods and other
regression techniques known to those skilled in the art.
Also included in these linearization methods is the
method disclosed in U.S. Patent Application Serial No.

25   09/350,747 filed on July 9, 1999, to T.I. Pattantyus,
et al., entitled "System and Method for Sensor Response
Linearization". Digitally linearized sensed flow signal
42 can be input into differentiation module 46.
Differentiation module 46 creates a digitally enhanced

30   flow rate signal 48. Digitally enhanced flow rate signal

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48 more accurately represents actual flow 24 and
compensates for the inaccuracies of sensor 26. A
detailed description of differentiation module 46 is
discussed later in the detailed description.

5   Digitally enhanced flow rate signal 48 is compared
with set-point signal 50. Set-point signal 50, provided
by a customer, may be a step input for the desired actual
flow 24. Set-point signal 50 may be either an analog
signal that is digitized by an embedded A/D converter in
10   microcontroller 44 or it can be a digital signal
transmitted to microcontroller 44. An embedded A/D
converter in microcontroller 44 allows microcontroller 44
of the present invention to be used as a drop-in
replacement in prior art systems. The difference between
15   set-point signal 50 and digitally enhanced flow rate
signal 48 is error signal 52. Error signal 52 may be
input to PI controller 54 to generate digital control
signal 56 that drives solenoid activated valve 58.
Solenoid activated valve 58 governs the actual flow 24 in
20   the mass flow controller 22. PI controller 54 may be
implemented using the method disclosed in U.S. Patent
Application Serial No. 09/351,098 filed on July 9, 1999,
to E. Vyers, entitled "System and Method for a Variable
Gain Proportional-Integral (PI) Controller."

25   Differentiation module 46 in FIGURE 3 represents the
process performed by microcontroller 44 using parameters
calculated by and downloaded from computer 55 to generate
digitally enhanced flow rate signal 48. The block
diagram within differentiation module 46 is a continuous-
30   time representation with Laplace transforms representing

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first differentiation operation 60, second
differentiation operation 68, and filter operation 72
having time constant τ_2. The system, however, is realized
digitally. Linearized digital sensor signal 42 is input
5   into first differentiation operation 60 and into first
gain stage 62 to output weighted first derivative 64 of
linearized digital sensor signal 42. Subsequently, the
first derivative of linearized digital sensor signal 42
is input into second differentiation operation 66 and
10   into gain stage 68 to create weighted second derivative
70 of linearized digital sensor signal 42. This weighted
second derivative 70 is input into lowpass filter
operation 72 to create filtered weighted second
derivative 74 of linearized digital sensor signal 42.
15   Weighted first derivative 64 is fed forward to adder 78
and linearized digital sensor signal 42 is fed forward
through feed forward loop 76 to adder 78. At adder 78,
filtered weighted second derivative 74 of linearized
digital sensor signal 42 is combined with weighted first
20   derivative 64 of linearized digital sensor signal 42 and
with linearized digital sensor signal 42 to construct
digitally enhanced flow rate signal 48. Digitally
enhanced flow rate signal 48 more closely represents
actual flow 24 in mass flow controller 22 than does
25   sensed flow rate signal 34 obtained from sensor 26.

     As stated previously, the operations performed by
microcontroller 44, a DSP, are realized digitally. A
one-to-one transformation between the analog Laplace
representations and their discrete-time counterpart can
30   be easily made. Linear constant coefficient differential

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equations can be easily transformed to discrete-time
linear constant coefficient difference equations. The
discrete equivalent of a constant coefficient
differential equation,

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$$\sum_{k=1}^{N} a_k \frac{d^k y(t)}{dt^k} = \sum_{k=1}^{M} b_k \frac{d^k f(t)}{dt^k} \; , \qquad\qquad \text{eqn. 4}$$

is

$$\sum_{k=1}^{N} a_k y[n-k] = \sum_{k=1}^{M} b_k f[n-k] \; , \qquad\qquad \text{eqn. 5}$$

10   where a_k and b_k are constant coefficients, f(t) is an
analog input into the analog system, y(t) is an analog
output of the analog system, $\frac{d^k y(t)}{dt^k}$ and $\frac{d^k f(t)}{dt^k}$ are the kth
derivatives of y(t) and f(t), f[n] is a discrete input
into the equivalent discrete system, y[n] is a discrete
15   output out of the equivalent discrete system, f[n-k] and
y[n-k] are the kth delay values of f[n] and y[n], t is
time, and n and k are the integer values representing
discrete samples of the discrete functions at a specified
sampling interval.

20   A continuous lowpass filter operation can also be
implemented in a discrete mode using difference
equations. The analog time domain representation of the
Laplace lowpass filter operation 72 is the differential
equation,

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$$f(t) = \frac{dy(t)}{dt} + \frac{1}{\tau_f} y(t) = \sum_{k=0}^{1} \frac{a_k}{b_k} \frac{dy^k(t)}{dt^k} \; , \qquad\qquad \text{eqn. 6}$$

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where a_k and b_k are constant coefficients, f(t) is an analog input into the filter, y(t) is an analog output of the filter, $\frac{d^k y(t)}{dt^k}$ is the kth derivatives of y(t) and τ_f is the time constant associated with the filter operation.

5   Eqn. 6 can be discretely realized using a difference equation according to eqn. 5. For the sake of simplicity, however, the system has been represented with the various Laplace transforms to illustrate the differentiation and filtering of the linearized digital

10   sensor signal 42.

First gain stage 62 (Gain 1) is designed to cancel the time constant τ_1 associated with sensor 26. First gain stage 62 is adjusted to correct for a sensor response from sensor 26 that takes a long time to settle.

15   FIGURE 4 illustrates the effects of varying first gain stage 62 on a continuous representation of digitally enhanced flow rate signal 48. If gain stage 62 is too small, there may be an initial overshoot before the continuous representation of digitally enhanced flow rate

20   signal 48 settles to the steady-state value. If gain stage 62 is too large, there may be an initial undershoot before the continuous representation of digitally enhanced flow rate signal 48 settles to the steady-state value. Due to the variability of the system, first gain

25   stage 62 is uniquely calculated for process gas species and a given mechanical platform. The first gain stage 62 is uniquely determined and is a function of the sensor construction and the process gas. Computational fluid dynamic (CFD) models, empirical testing and mathematical

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solution have been developed primarily in an effort to
minimize the time constant τ_1 of the sensor. The
relationship of temperature rise, coil length, gap
between coils, tube internal diameter, tube wall

5   thickness, tube thermal conductivity and insulation were
analyzed and will be further discussed. Practically
speaking, one sensor employed by one embodiment of the
present invention displays a 1.7s time constant τ_1. The
gas type effect displays a tendency for the sensor time

10   constant τ_1 to increase in proportion to the gas weight
(typically 5% at most). The time constant τ_1 is set to a
default value (1.7) and fine tuned by observation of the
actual response.

Since sensed flow rate signal 34 is not a true

15   exponential signal, first weighted derivative 64 does not
completely correct sensed flow rate signal 34 to
accurately approximate actual flow 24. To more accurately
approximate actual flow 24, a second time constant τ_2 is
incorporated in the approximation of sensed flow rate

20   signal 34. Therefore, sensed flow rate signal 34 can be
approximated as

$$f(t)=(1-e^{-t/\tau_1})(1-e^{-t/\tau_2})$$ eqn. 7

25   where t is time, f(t) is sensed flow rate signal 34, τ_1 is
a first time constant and τ_2 is a second time constant.
Assuming a steady-state step input f_0 and according to
FIGURE 3, digitally enhanced flow rate signal 48 can be
represented in the analog domain as

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$$f(t) + (\text{Gain } 1)\frac{df(t)}{dt} + (\text{Gain } 2)\frac{d^2f(t)}{dt^2}$$

with Gain 1 = $\tau_1 + \tau_2$ and Gain 2 = $\tau_1 * \tau_2$. The time lags that
can contribute to τ_1 and τ_2 are pneumatic lag between
sensor 26 and the seat of solenoid-activated valve 58 and
to a limited extent the solenoid activating solenoid
activated-valve 58 when dealing with hysterisis, friction
and line pressure dependent preload forces holding the
seat shut of solenoid-activated valve 58.

Therefore, second derivative operation 66 is
implemented with the corresponding second gain stage 68
(Gain 2). Second derivative operation 66 corrects for
the front end of the sensed flow rate signal 34 which
does not accurately approximate a true exponential rise.
As with first gain stage 62, second gain stage 68 is
adjustable by programming. FIGURE 5 illustrates the
effects of varying second gain stage 68 on a continuous
representation of digitally enhanced flow rate signal 48.
If second gain stage 68 is small, there may be an initial
overshoot before the continuous representation of
digitally enhanced flow rate signal 48 settles to the
steady-state value, while if second gain stage 68 is
large, there may be an initial undershoot of the signal
before the continuous representation of digitally
enhanced flow rate signal 48 settles to the steady-state
value. Thus, second gain stage 68 can be properly
calibrated to minimize or eliminate overshoot or

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undershoot. Second gain stage 68 is also adjusted by
observation as described above.

Lowpass filter operation 72 is implemented to reduce
the noise generated in digitally enhanced flow rate
5   signal 48 when implementing second differentiation
operation 66. Lowpass filter operation 72 has associated
time constant τ_f. By adjusting time constant τ_f, the
response of lowpass filter operation 72 can be over-
corrected or under-corrected. FIGURE 6 illustrates the
10   effects of varying time constant τ_f on a continuous
representation of digitally enhanced flow rate signal 48.
For large filter time constant τ_f, the filter response may
be too slow, while for a small filter time constant τ_f,
the filter response may be too fast. The filter time
15   constant τ_f is chosen to adjust the speed of signal 48.

The system in FIGURE 3 may also use a computer 55 to
perform rigorous computations that require more speed and
power than that available in microcontroller 44 during
calibration and test. Computational results can be
20   downloaded from computer 55 to microcontroller 44 via
electrical communication connection 57, such as a bus or
cable.

Overall, the system of FIGURE 3 may be realized
easily by implementing a thermal flow sensor with
25   conditioning circuitry with -1.7 second primary time
constant. Reference is made to the flow sensor circuitry
disclosed in U.S. Patent Application Serial No.
09/350,746 filed July 9, 1999 by T.I. Pattantyus et. al.,
entitled "Improved Mass Flow Sensor Interface Circuit."
30   A 16-bit-accuracy A/D converter with a sampling rate of

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610 Hz, a 16-bit digital signal processor
microcontroller, a PC, and pulse width modulated or
continuous valve drive circuitry which controls the a
solenoid-activated, low power, throttling ball/seat valve
5   can also be included. Many circuit configurations can be
implemented for the valve drive circuitry. Reference is
made to the circuitry disclosed in U.S. Patent
Application Serial No. 09/351,111 filed on July 9, 1999,
to T.I. Pattantyus, entitled "Method and System for
10   Driving a Solenoid"

Mass flow controllers can implement a closed loop
control algorithm. Reference is made to the advanced
digital control algorithm disclosed in U.S. Patent
Application Serial No. 09/350,744 filed on July 9, 1999
15   by K. Tinsley entitled "System and Method of Operation of
a Digital Mass Flow Controller".

A major technical advantage of the present invention
is that it is realized in the discrete-time domain.
Rigorous mathematical computations can be performed or
20   aided by computer 55. Although some prior art methods
implement discrete controllers, these methods typically
do not possess digital platforms with the power to
generate the mathematics which include both a first and a
second derivative. Consequently, these methods are
25   limited to digital implementations of the first
derivative. Through the use of a powerful computer 55,
however, the present invention is able to perform
rigorous mathematical computations. Parameter
calculations such as first gain stage 62, second gain
30   stage 68, and time constant τ_f can be worked out on

computer 55 and then downloaded into an erasable memory
array such as an EEPROM in microcontroller 44.
Microcontroller 44 then can access these values from the
EEFROM when calculating digitally enhanced flow rate

5   signal 48.

Another important technical advantage of the present
invention is that with the implementation of second
differentiation operation 66, digitally enhanced flow
rate signal 48 closely approximates actual flow 24.

10   Since sensed flow rate signal 34 is not a pure
exponential signal, implementation of the first
differentiation operation 60 alone does not sufficiently
approximate actual flow 24. Weighted first derivative 64
and weighted second derivative 70 accelerate the response

15   of the sensed flow rate signal 34 to more closely
approximate actual flow 24. Subsequent filtering of
weighted second derivative 70 reduces noise associated
with implementing second differentiation operation 66.

Still yet another technical advantage of the present

20   invention is that through the use embedded A/D converters
in microcontroller 44, microcontroller 44 can easily
replace prior art systems used to control gas in a
manufacturing process. These processes, which may have
used analog methods and continuous set-point voltage

25   inputs to control the gas flow, can still use
microcontroller 44. The analog signals, such as sensed
flow rate signal 34 and set-point signal 50, are
digitized and then used for computations in
microcontroller unit 44.

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Although the present invention has been described in
detail herein with reference to the illustrative
embodiments, it should be understood that the description
is by way of example only and is not to be construed in a
5   limiting sense. It is to be further understood,
therefore, that numerous changes in the details of the
embodiments of this invention and additional embodiments
of this invention will be apparent to, and may be made
by, persons of ordinary skill in the art having reference
10   to this description. It is contemplated that all such
changes and additional embodiments are within the spirit
and true scope of this invention as claimed below.

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WHAT IS CLAIMED IS:

1.   A method for controlling a gas flow within a digital mass flow controller having a valve that governs the flow rate of gas in said digital mass flow controller and a flow sensor that measures an actual gas flow rate through said digital mass flow controller and outputs a sensed flow rate signal, said method comprising:

generating a digitally enhanced flow rate signal representing a final steady-state flow rate in said digital mass flow controller based on a summation of a weighted first derivative of said sensed flow rate signal, a filtered weighted second derivative of said sensed flow rate signal, and said sensed flow rate signal;

comparing a set-point signal with said digitally enhanced flow rate signal to generate a digital feedback error signal; and

generating a digital control signal that controls said valve in said digital mass flow controller by inputting said digital feedback error signal into a proportional integral (PI) controller and outputting from said PI controller said digital control signal.

2.   The method of Claim 1, further comprising the step of converting said sensed flow rate signal to a digital sensed flow rate signal using an A-to-D converter prior to generating said digitally enhanced flow signal.

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3.   The method of Claim 2, further comprising the
step of converting said digital sensed flow rate signal
to a digitally linearized sensed flow rate signal using a
least squares method prior to generating said digitally
5   enhanced flow rate signal.

4.   The method of Claim 3, further comprising the
step of weighting a first derivative with a first weight
to generate said weighted first derivative, said first
10   weight is uniquely calculated based on a gas species in
said digital mass flow controller and a given mechanical
platform.

5.   The method of Claim 4, further comprising the
15   step of weighting a second derivative with a second
weight, to generate said weighted second derivative, said
second weight is calculated to correct where said
digitally linearized sensed flow rate signal does not
approximate a true exponential rise.
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6.   The method of Claim 5, further comprising the
step of implementing a digital lowpass filter operation
to filter said weighted second derivative to generate
said filtered weighted second derivative and compensate
25   for noise added to said digitally enhanced signal due to
said weighted second derivative.

7.   The method of Claim 6, wherein said digital
lowpass filter operation further comprises a time
30   constant, said time constant is determined empirically.

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8.   The method of Claim 7, further comprising the
step of converting said set-point signal to a digital
set-point signal prior to the step of comparing said set-
5   point signal with said digitally enhanced flow rate
signal.

9.   The method of Claim 8, wherein the steps of
generating said digitally enhanced flow rate signal,
10   comparing said set-point signal with said digitally
enhanced signal, and generating said digital control
signal are executed by a digital signal processor
controller.

15   10.   The method of Claim 9, wherein said digital
signal processor controller is executable to communicate
with a computer, said computer is executable to perform
calculations including said first weight, said second
weight, and said time constant.
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11.   The method of Claim 10, further comprising the
step of downloading calculations performed by said
computer to a storage device in said digital signal
processor controller via a connection between said
25   computer and said digital signal processor controller to
aid said digital signal processor controller in
calculating said digital control signal.

12.   The method of Claim 11, wherein said storage
30   device is a EEPROM.

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13.   The method of Claim 1, wherein said weighted
first derivative, said filtered weighted second
derivative, said digitally enhanced flow rate signal, and
5   said digital control signal are calculated using
difference equations.

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14. A method for generating a digitally enhanced
flow rate signal that represents a final steady-state
flow rate from a sensed flow rate signal provided by a
flow sensor in a digital mass flow controller, said
5   method comprising:
        calculating a first derivative of said sensed flow
rate signal;
        calculating a second derivative of sensed flow rate
signal;
10   weighting said first derivative with a first weight
to generate a weighted first derivative signal;
        weighting said second derivative with a second
weight to generate a weighted second derivative;
        implementing a digital lowpass filter operation on
15   said weighted second derivative to generate a filtered
weighted second derivative; and
        summing said sensed flow rate signal with said
weighted first derivative signal and said filtered
weighted second derivative signal to generate said
20   digitally enhanced flow rate signal.

15. The method of Claim 14, further comprising the
step of converting said sensed flow rate signal to a
digital sensed flow rate signal prior to the steps of
25   calculating said first derivative and calculating said
second derivative.

16. The method of Claim 15, further comprising the
step of converting said digital sensed flow rate signal
30   to a digitally linearized sensed flow rate signal using a

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least squares method prior to the steps of calculating
said first derivative and calculating said second
derivative.

5   17.   The method of Claim 16, wherein said first
weight for said weighted first derivative is calculated
based on a gas species in said digital mass flow
controller and a given mechanical platform.

10   18.   The method of Claim 17, wherein said second
weight for said weighted second derivative is calculated
to correct where said digitally linearized sensed flow
rate signal does not approximate a true exponential rise.

15   19.   The method of Claim 18, wherein said digital
lowpass filter operation further comprises a time
constant determined empirically.

            20.   The method of Claim 19, wherein the steps of
20   calculating said first derivative, calculating said
second derivative, weighting said first derivative,
weighting said second derivative, implementing said
digital lowpass filter operation, and summing said sensed
flow rate signal with said weighted first derivative and
25   said weighted second derivative are executed by a digital
signal processor controller.

            21.   The method of Claim 20, wherein said digital
signal processor controller is executable to communicate
30   with a computer via a connection between said digital

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signal processor controller and said computer, said
computer is executable to perform calculations including
said first weight, said second weight, and said time
constant.

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22. The method of Claim 21, further comprising the
step of downloading calculations performed by said
computer to a storage device in said digital signal
processor controller to aid said digital signal processor
10   controller in calculating said digitally enhanced flow
rate signal.

23. The method of Claim 22, wherein said storage
device is a EEPROM.

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24. The method of Claim 13, wherein said weighted
first derivative, said filtered weighted second
derivative, and said digitally enhanced flow rate signal
are calculated using difference equations.

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25.   A digital mass flow controller for controlling
the flow of gas in a process, said digital mass flow
controller comprising:

a flow sensor that measures an actual gas flow rate
5   through said digital mass flow controller and outputs a
sensed flow rate signal;

a digital microcontroller which generates a digital
control signal using said sensed flow rate signal, a
first derivative of said sensed flow rate signal, a
10   filtered second derivative of said sensed flow rate
signal, and a set-point signal; and

a valve in said digital mass flow controller which
is controlled by said digital control signal.

15   26.   The system of Claim 25, wherein said
microcontroller is executable to:

calculate said first derivative of said sensed flow
rate signal;

calculate a second derivative of said sensed flow
20   rate signal;

weight said first derivative with a first weight to
generate a weighted first derivative;

weight said second derivative with a second weight
to generate a weighted second derivative;

25   implement a digital lowpass filter operation on said
weighted second derivative to generate a filtered
weighted second derivative; and

sum said sensed flow rate signal with said weighted
first derivative signal and said weighted second

29

derivative signal to generate a digitally enhanced flow
rate signal.

27. The system of Claim 26, wherein said sensed
5   flow rate is converted to a digital sensed flow rate
signal prior to:
        calculating said first derivative;
        calculating said second derivative; and
        summing said digital sensed flow rate signal with
10   said weighted first derivative signal and said weighted
second derivative signal.

28. The system of Claim 27, wherein said digital
sensed flow rate signal is converted to a digitally
15   linearized sensed flow rate signal using a least squares
method prior to:
        calculating said first derivative;
        calculating said second derivative; and
        summing said digital sensed flow rate signal with
20   said weighted first derivative signal and said weighted
second derivative signal.

29. The system of Claim 28, wherein said first
weight is calculated based on gas species in said digital
25   mass flow controller and a given mechanical platform.

30. The system of Claim 29, wherein said second
weight is calculated to correct where said digitally
linearized sensed flow rate signal does not approximate a
30   true exponential rise.

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31.   The system of Claim 30, wherein said digital
lowpass filter operation further comprises a time
constant which is determined empirically.

5

32.   The system of Claim 31, wherein said digital
microcontroller is further executable to:
     compare said set-point signal with said digitally
enhanced flow rate signal to generate a digital error
10   signal; and
     implement a digital PI (proportional integral)
control operation on said digital error signal to
generate a digital control signal.

15   33.   The system of Claim 25, wherein said set-point
signal is a digital signal.

34.   The system of Claim 32, wherein said set-point
signal is converted to a digital set-point signal prior
20   to comparing said set-point signal with said digitally
enhanced flow rate signal.

35.   The system of Claim 34, wherein said digital
microcontroller is a digital signal processor
25   microcontroller.

36.   The system of Claim 35, wherein said digital
signal processor microcontroller is executable to
communicate with a computer via a connection between said
30   computer and said digital signal processor controller,

said computer is executable to perform calculations including said first weight, said second weight, and said time constant.

5   37. The system of Claim 36, wherein said computer is further executable to download said calculations performed by said computer to a storage device in said digital signal processor controller to aid said digital signal processor controller in calculating said digital
10   control signal.

38. The system of Claim 37, wherein said storage device is an EEPROM.

15   39. The system of Claim 26, wherein said weighted first derivative, said weighted second derivative, said filtered weighted second derivative, and said digital control signal are calculated using difference equations.

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40. A system for generating a digitally enhanced flow rate signal from a sensed flow rate signal provided by a flow sensor in a mass flow controller, said system having a computer program stored on a digital signal

5   processor controller, said digital signal processor controller executable to:

calculate a first derivative of said sensed flow rate signal;

calculate a second derivative of sensed flow rate

10   signal;

weight said first derivative with a first weight to generate a weighted first derivative signal;

weight said second derivative with a second weight to generate a weighted second derivative;

15   implement a digital lowpass filter operation on said weighted second derivative to generate a filtered weighted second derivative; and

sum said sensed flow rate signal with said weighted first derivative signal and said filtered weighted second

20   derivative signal to generate said digitally enhanced flow rate signal.

41. The system of Claim 40, wherein said sensed flow rate is converted to a digital sensed flow rate

25   prior to calculating said first derivative, calculating said second derivative, and summing said sensed flow rate signal with said weighted first derivative and said filtered weighted second derivative.

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42. The system of Claim 41, wherein said digital sensed flow rate is converted to a digitally linearized sensed flow rate using a least squares method prior to calculating said first derivative, calculating said

5   second derivative, and summing said sensed flow rate signal with said weighted first derivative and said filtered weighted second derivative.

43. The system of Claim 42, wherein said first

10   weight for said weighted first derivative is calculated based on a gas species in said digital mass flow controller and a given mechanical platform.

44. The system of Claim 43, wherein said second

15   weight for said weighted second derivative is calculated to correct where said digitally linearized sensed flow rate signal does not approximate a true exponential rise.

45. The system of Claim 44, wherein said digital

20   lowpass filter operation further comprises a time constant, said time constant is empirically determined.

46. The system of Claim 45, wherein said digital signal processor controller is executable to communicate

25   with a computer via a connection between said digital signal processor controller and said computer, said computer is executable to perform calculations including said first weight, said second weight, and said time constant.

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47. The system of Claim 46, wherein said computer is further executable to download calculations performed by said computer to a storage device in said digital signal processor controller to aid said digital signal
5 processor controller in generating said digitally enhanced flow rate signal.

48. The system of Claim 47, wherein said storage device is an EEPROM.
10

49. The system of Claim 40, wherein said weighted first derivative, said weighted second derivative, and said filtered weighted second derivative are calculated using difference equations.
15

FLOW
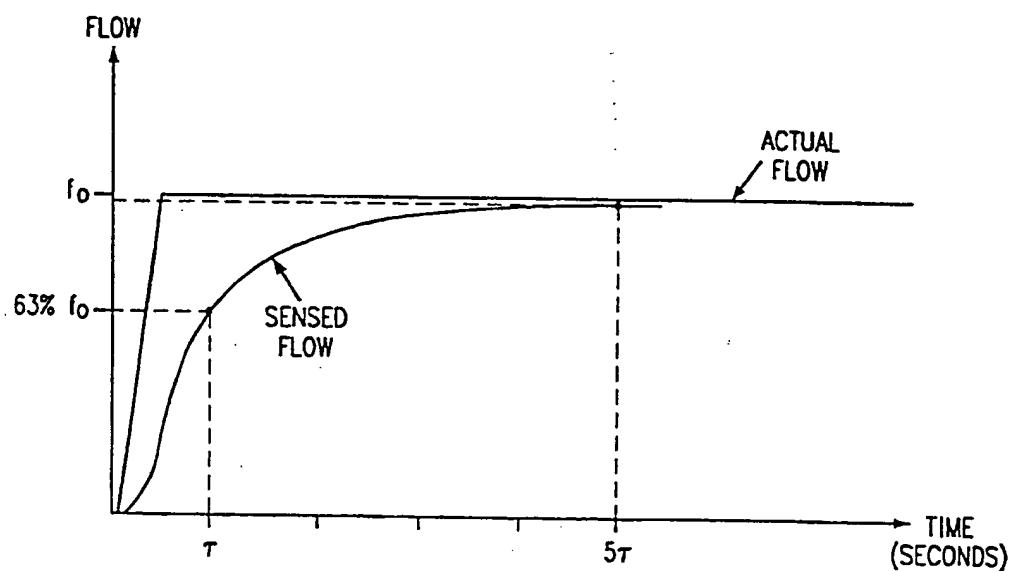
FIG. 1
(PRIOR ART)
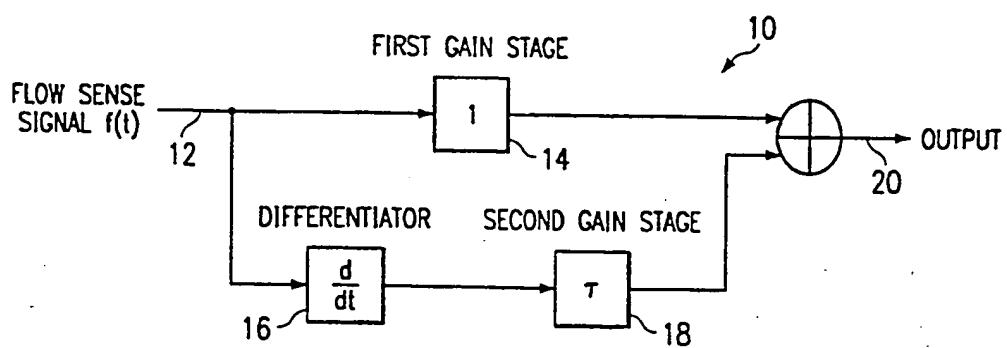
FIG. 2
(PRIOR ART)

FIG. 3

FIG. 4

FIG. 5

FIG. 6
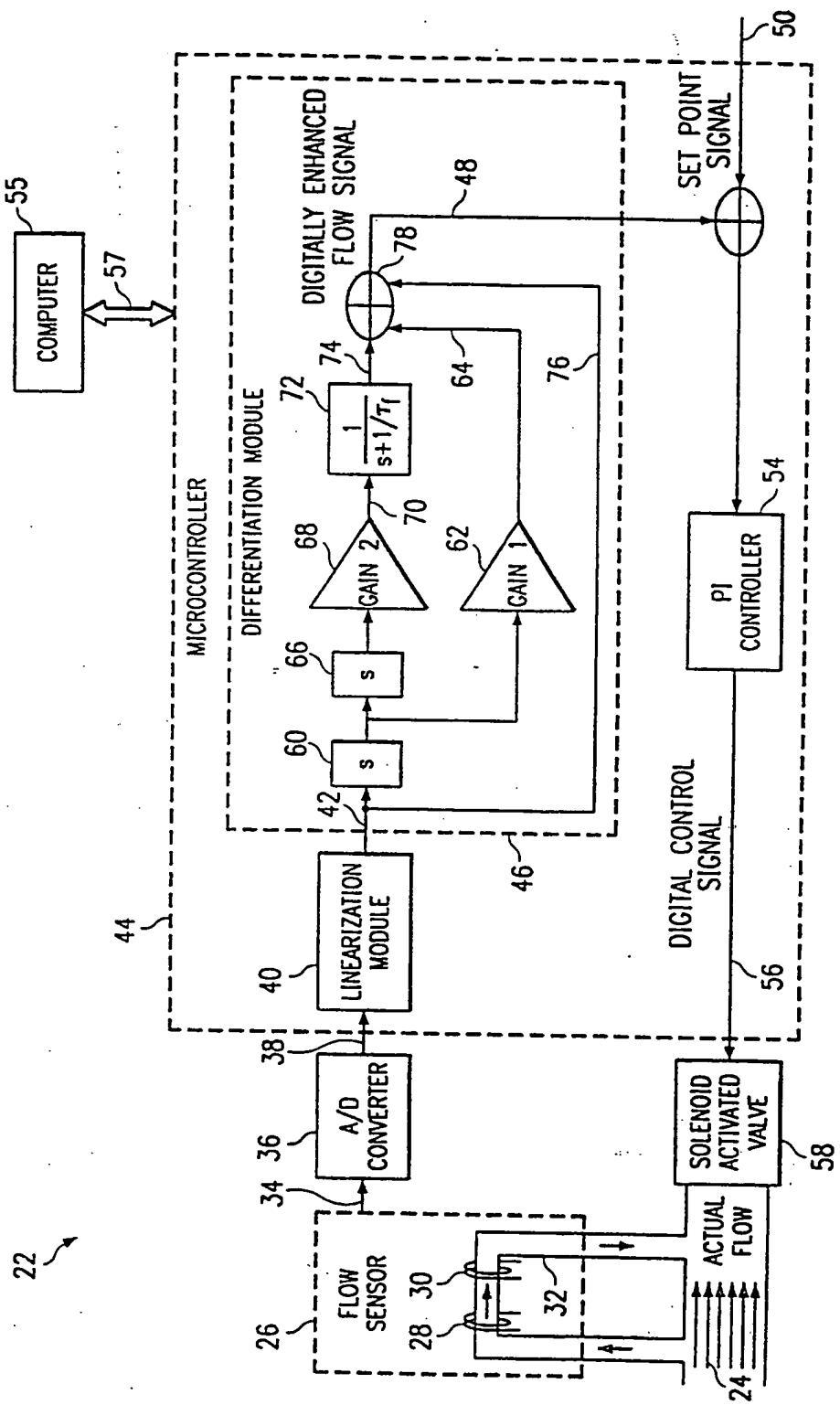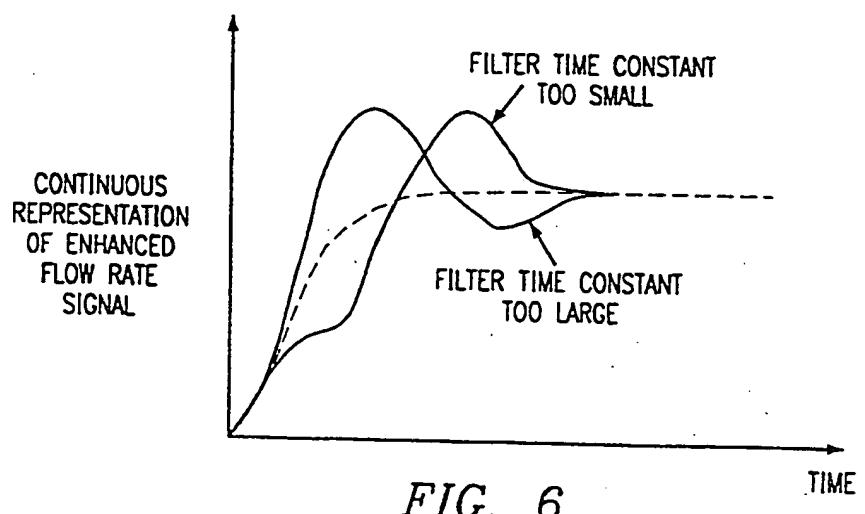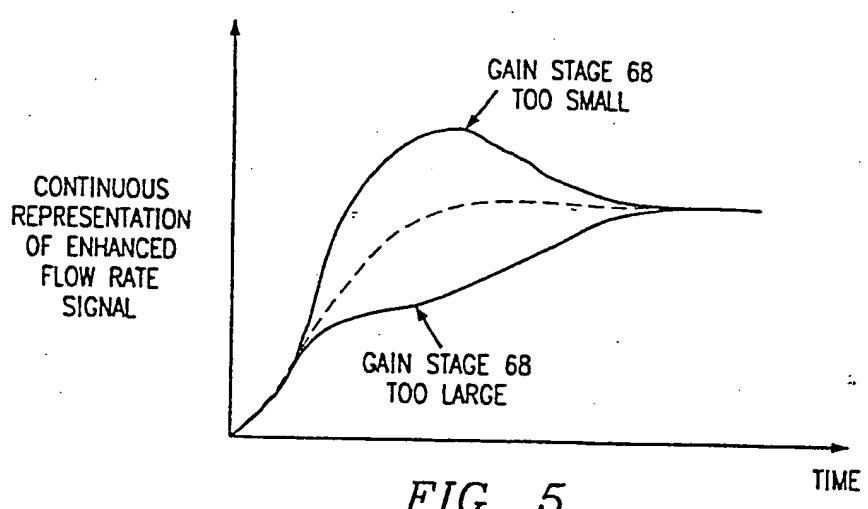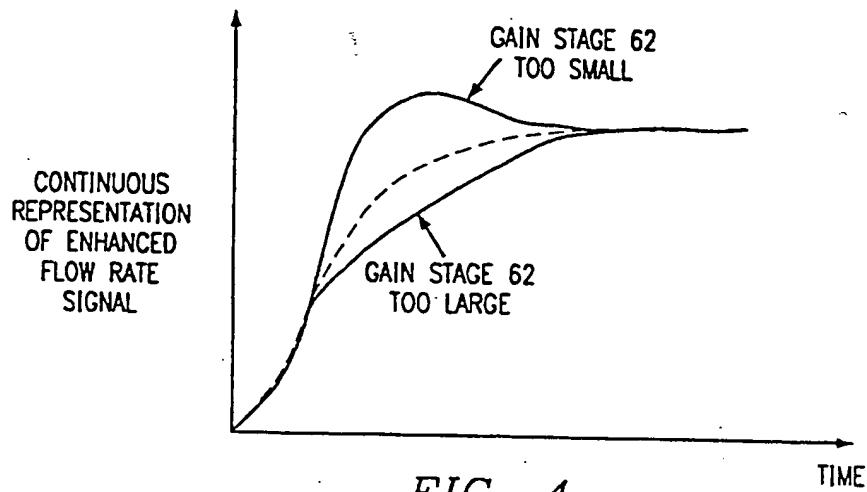
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G05D7/06   G01F1/56

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   G05D   G01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 632 085 A (MISAWA MITSUKUNI ET AL) 30 December 1986 (1986-12-30) abstract; figure 1 column 2, line 15 -column 3, line 20; figure 1	1,14,25, 40
A	DE 30 05 414 A (DAIMLER BENZ AG) 20 August 1981 (1981-08-20) page 8, line 1 - line 18; figure 1	1,14,25, 40

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

27 October 2000

Date of mailing of the international search report

07/11/2000

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Information on patent family members

Int .tional Application No
PCT/US 00/40251

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 4632085	A	30-12-1986	JP	60178915 A	12-09-1985
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